

# NUMERICAL MODELLING OF TRANSITION REGION DYNAMICS

L. TERIACA AND J. G. DOYLE

*Armagh Observatory*

*Armagh BT61 9DG, N. Ireland*

**Abstract.** We explore the idea that the occurrence of nano-flares in a magnetic loop around the O VI formation temperature could explain the observed red-shift of mid-low transition region lines as well as the blue-shift observed in low coronal lines ( $T > 6 \times 10^5$  K). Observations are compared to numerical simulations of the response of the solar atmosphere to an energy perturbation of  $4 \times 10^{24}$  ergs representing an energy release during magnetic reconnection in a 1-D semi-circular flux tube. The temporal evolution of the thermodynamic state of the loop is finally converted into C III 977, C IV 1548, O V 630, O VI 1032, Ne VII 465 and Ne VIII 770 line profiles in non-equilibrium ionization. Performing an integration over the entire period of simulation, redshifts of 8.5, 6.1 and 1.7 km s<sup>-1</sup>, are found in C III, C IV, and O V while blue-shifts of -1.8, -3.9 and -10.7 km s<sup>-1</sup> were derived for O VI, Ne VII and Ne VIII respectively, in good agreement with observations.

## 1. Introduction

During the last two decades, observations of red-shifted emission lines formed at transition region (TR) temperatures were obtained by many authors using several UV instruments with different spatial resolution (see Brekke et al. 1997 and references therein). Brekke et al. (1997) and Chae et al. (1998) have shown that for the ‘quiet’ Sun the red-shift is peaked around  $1.5 \times 10^5$  K with a value of  $\sim 11$  km s<sup>-1</sup>. Peter & Judge (1999) found *blue-shifts* at disk center for three coronal lines (i.e., Ne VIII at 770 Å and 780 Å and Mg X at 625 Å). Recently, Teriaca et al. (1999a) found evidence for *blue-shift* in both the ‘quiet’ Sun and in an active region at upper TR and coronal temperatures. Here we investigate the consequences of these observational results via a comparison with numerical studies.

## 2. Observational Results

Teriaca et al. (1999a) have shown that the temperature variations of the Doppler shifts and non-thermal velocities in the ‘quiet’ Sun and active region have important implications for the validity of the physical models for the red-shift (or down-flow) problem. In Fig. 1 we show the behaviour of the Doppler shift versus temperature of formation for an active region as reported by Teriaca et al. (1999a). From their measurements it is possible to infer that the reversal from red-shift to blue-shift takes place around  $\log T = 5.7$  in the active region while in the ‘quiet’ Sun a value between  $\log T = 5.7$  and  $\log T = 5.75$  can be estimated (Teriaca et al. 1999a).

## 3. Modelling

For the redshift problem, Hansteen (1993) presented a physical model, considering nano-flares occurring at the top of coronal loops, generating MHD waves that propagate downward along the magnetic fields towards and through the transition region.

This model was extended by Hansteen et al. (1996) including the reflection that the chromosphere exerts on the downward travelling waves. This model is able (as also pointed out by Peter & Judge 1999) to explain the presence of blue-shift together with red-shift within one model.

Following the suggestion of Peter & Judge (1999) we support the idea of the prevalent occurrence of magnetic reconnection around the O VI formation temperature ( $3 \times 10^5$  K) as a source for the red-shift observed in the low and middle transition region and for the blue-shift seen in the upper transition region and coronal lines.

In the present work the small-scale energy depositions are simulated in a one-dimensional semi-circular rigid magnetic flux tube (see, e.g., Sterling et al. 1991, 1993; Mariska 1992; Sarro et al. 1999; Teriaca et al. 1999b). After the hydrodynamics variables are computed, we calculate the ion populations for three different elements, and finally a line synthesis program gives UV line profiles suitable for comparison with observations.

## 4. Observational Consequences

In order to calculate the ion populations along the loop for a given time we have to integrate the ionization equations, i.e.,

$$\frac{\partial N_i}{\partial t} + \frac{\partial(N_i \cdot v)}{\partial s} = N_e(N_{i+1}\alpha_{i+1} + N_{i-1}S_{i-1} - N_i(\alpha_i + S_i)) \quad (1)$$

where  $\alpha_i$  and  $S_i$  are the recombination and ionization coefficients of ionization stage  $i$  and  $N_i$  is the volume number density of ion  $i$ .

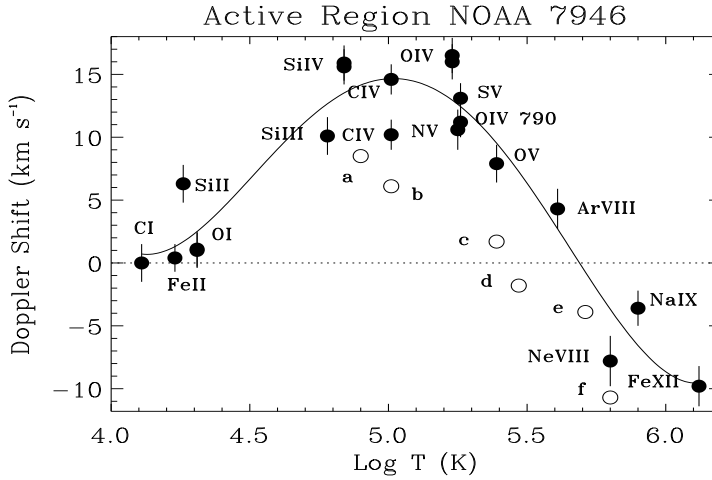


Figure 1. SUMER measurement of radial velocities in active region NOAA 7946 (full dots). The solid line represent a polynomial fit (Teriaca et al. 1999a). Empty circles represents the amount of shift showed by the line profiles of C III 977 (a), C IV 1548 (b), O V 630 (c), O VI 1032 (d), Ne VII 465 (e) and Ne 770 (f) when an integration over the entire duration of the simulation is performed.

Once the ion populations are computed, the emissivity of a given emission line per unit interval of wavelength in an optically thin, collisionally excited line can be obtained by using the standard equation

$$E_{\lambda} \propto \frac{hc}{\lambda} \frac{\Omega}{\omega} \frac{N_1}{N_{\text{ion}}} \frac{N_{\text{ion}}}{N_{\text{elem}}} \frac{N_{\text{elem}}}{N_{\text{H}}} N_{\text{H}} N_{\text{e}} \frac{\exp \frac{-W}{k_{\text{b}} T}}{\sqrt{T}} \phi(\lambda) \quad (2)$$

For allowed transitions (e.g. C IV 1548, O VI 1032 and Ne VIII 770) the bulk of the population of the ions resides in the ground level. This means that is possible to assume that  $N_1/N_{\text{ion}} = 1$ . The other 3 ions considered here (i.e. C III, O V and Ne VII) belong to the beryllium isoelectronic sequence. Beryllium-like ions contain metastable levels and the strong resonance transition  $2s^2 \ ^1S_0 - 2s2p \ ^1P_1$  give rise to some of the most prominent lines in solar and stellar spectra (e.g. C III 977, O V 630 and Ne VII 465). In these cases the level population need to be evaluated as a function of the electron density and temperature. The population of the ground level has, hence, been calculated using the CHIANTI database and the related software (Landi & Landini, 1998; Landini & Monsignori Fossi 1990).

Given a distribution of emissivities along the loop, the total intensity

can be calculated as

$$I_{\lambda} = \int_0^{s_e} E_{\lambda} ds \quad (3)$$

where  $s_e$  is the total length of the loop.

## 5. Numerical Results

In the results shown in Fig. 1, an energy input of  $4 \times 10^{24}$  ergs was released at an height of 5400 km (corresponding to  $\log T = 5.7$ ) in a 1-D magnetic loop. The temporal evolution of the thermodynamic state of the loop is converted into C III 977 Å, C IV 1548 Å, O V 630 Å, O VI 1032 Å, Ne VII 465 Å and Ne VIII 770 Å line profiles (see Teriaca et al. 1999b).

Performing an integration over the entire period of simulation (55 seconds), redshifts of 8.5, 6.1 and 1.7 km s<sup>-1</sup>, are found in C III, C IV, and O V while blue-shifts of 1.8, 3.9 and 10.7 km s<sup>-1</sup> were derived for O VI, Ne VII and Ne VIII respectively, in good agreement with observations (see Fig. 1).

We trust our results shed further light into the physics and modelling of the complexity of the solar (and stellar) transition region. We plan to develop the modelling of the nano-flare mechanism exploring in detail the parameter space, calculating the response of the model to different amount of deposited energy at different temperatures.

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